Assessing Winter Wheat Dry Matter Production Via Spectral Reflectance Measurements

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The objectives for this study were (1) to investigate the potential usefulness of growing-season spectral measurements in order to predict end-of-season winter wheat dry-matter production and (2) to evaluate straw–total-dry-matter relationships and their possible usefulness in residue management decisions A field experiment was located on a Williams loam soil (fine–loamy mixed, Typic Argiborolls), 11 km northwest of Sidney, Montana "Roughrider," a winterhardy hard red winter wheat (*Triticum aestivum* L) cultivar, was seeded to seven stands of from 0 to 100% (100% = 1,570,000 plants per hectare) On clear mornings, a handheld radiometer was used to measure reflectances, corresponding to the Landsat multispectral scanner bands Grain and straw yield data were collected to determine the degree of relationship between grain and dry matter Relationships between the normalized difference vegetation index [ND7 = (MSS7 − MSS5)/(MSS7 + MSS5)] as determined from late tillering until the beginning of flowering growth stages, and end-of-season straw and total dry matter clearly established the potential of remote sensing for predicting straw and total dry-matter yield Predicting dry-matter production is useful in providing an estimate of residue production for erosion control and as a potential source for feed and energy

Introduction

If successfully applied, remote sensing of biomass can be important in global predictive estimates of grain production, total above ground biomass production, and, by inference, CO_2 balance. Perhaps the most comprehensive and best known effort in remote sensing of field crops was the Large Area Crop Inventory Experiment (LACIE), undertaken by NASA and cooperating agencies (Bauer et al., 1979; MacDonald and Hall, 1980)

Using Landsat data, Harlan and Liu (1975) showed that winter wheat growth and yield are related to seasonal radiance measurements Moraın and Williams (1975) used a combination of satellite and traditional methods in discussing winter wheat crop areas and production forecasts.

Leafy material dominates the wheat plant biomass until the end of tillering, corresponding to Feekes growth stage 5 (Large, 1954), during which time there is a strong relationship between leaf area and total above ground dry matter (Aase, 1978) However, Aase established that past stage 5, a close correlation exists only between leaf dry matter and leaf area. This relationship was recently verified by LeMaster et al. (1980). Because of this relationship, leaf dry matter can be substituted for leaf-area index in wheat plant growth and yield models requiring leaf area indices. Good relationships have been found between leaf-area index and/or leaf dry matter and reflectance measurements for wheat (Wiegand et al., 1979, Aase and Siddoway, 1980b, 1981) as well as for other crops (Holben et al., 1980) Daughtry et al (1980) discussed the influence of cultural factors on reflectance from spring wheat canopies

Tucker et al (1980a, 1980b) discussed the predictive potential of reflectance

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measurements during the growing season for winter wheat grain and total dry-matter production. Aase and Siddoway (1981) evaluated the predictive relationship between vegetation indices, as determined during the growing season, and grain and end-of-season dry-matter yields and also discussed implications for residue management and control.

For proper residue management, estimates of crop residues must be reasonably accurate. Crop residues are needed to maintain and build up organic matter in the soil and to control wind and water erosion (American Society of Agronomy, 1978). Proposals have also been made to use excess residues for energy conversion. Tucker et al. (1980b) approached the problem of estimating total dry-matter production in relation to the global CO_2 cycle and proposed a satellite system to allow for large area assessments of net primary phytomass production.

The most direct method to obtain residue information is field sampling, which is tedious, time consuming, and not practical for large areas. Residues can be estimated indirectly from grain yields by assuming constant straw:grain ratios. Bauer and Zubriski (1978) discussed this indirect approach and the potential predictive value of straw (residue) yield from straw:grain ratios.

Our objectives were: (1) to investigate the potential usefulness of growing-season spectral measurements to predict end-of-season winter wheat straw and total dry-matter production, and (2) to evaluate the straw–total dry-matter relationship and its possible usefulness in residue management decisions.

Materials and Methods

The field study was located on a Williams loam (fine-loamy mixed, Typic Argiborolls) site 11 km northwest of Sidney, Montana (47°46′N, 104°15′W). "Roughrider," a winterhardy hard red winter wheat (*Triticum aestivum* L.) cultivar, was seeded at seven rates (0, 10, 20, 40, 60, 80, and 100%, where 100% = 67 kg/ha) with a deep-furrow drill on 14 September 1977. Furrows were 5 cm deep and 30 cm apart in a north–south direction, plots were 20 m × 20 m, arranged with three sets of seeded plots on the east and west of a central alley. The bare plot was located southeast of the seeded plots. All plots were seeded to stand, except the 10% plot which was hand-thinned from a 20% seeded stand. Phosphorus fertilizer had previously been added to ensure an adequate supply, and 39 kg/ha of nitrogen was broadcast with the drill.

An Exotech[1] Model 100-A Radiometer with a 15° field of view (FOV) was used to measure spectral band reflectances corresponding to the Landsat multispectral scanner (MSS) bands 4, 5, 6, and 7, representing wavelengths of 0.5 to 0.6, 0.6 to 0.7, 0.7 to 0.8, and 0.8 to 1.1 μm, respectively. All channel outputs were read simultaneously and recorded on a portable battery-operated digital printer, and later manually read and transferred for analysis. Because the morning hours generally are the clearest, with scattered cumulus clouds commonly beginning to move in from the west after about 1000 MST, we sampled at 0930 and completed the measurements in less than 10 min. Readings were taken on clear days and on days with apparent haze or distant horizon cumulus clouds, which seemed not to interfere with the solar beam.

[1] Trade names or company names are included for the benefit of the reader and imply no endorsement or preferential treatment by the U.S. Department of Agriculture of the product listed.

Sampling consisted of two dark-level readings (background reading allowing no light to enter lenses), four readings from a painted barium sulfate standard[2] and six readings from each of the plots in the following sequence. dark level, standard, bare soil, standard, standard, 100% plot, 10% plot, standard, 20% plot, 80% plot, standard, 40% plot, 60% plot, standard, standard, bare soil, standard, and dark level. Reflectance factors were determined by dividing crop and soil radiances by the barium sulfate standard radiance

The barium sulfate standard (58 cm × 58 cm) was transported during the measurements to three conveniently located predetermined spots and placed on three preleveled wooden stakes extending about 20 cm above ground level

To facilitate the reflectance measurements within each plot, planks were placed on 20-cm-high concrete blocks The planks, with one end adjacent to the north–south central alley, extended about 6 m into the plot perpendicularly to the rows Three readings were taken from predetermined sampling locations on each side of the plank. The radiometer reflectance readings subtended an area about 50 cm in diameter at ground level.

Because of the simplicity of the MSS7/MSS5 ratio and the fact that it may have merit in describing growth patterns (Tucker, 1979, Tucker et al , 1980b), we compared this ratio with the normalized difference vegetation index (ND7) of Rouse et al (1973) and Deering et al. (1975) where

$$ND7 = (MSS7 - MSS5)/(MSS7 + MSS5).$$

[2]Manufactured and calibrated by Robert J Reginato, U S Water Conservation Laboratory, Phoenix, Arizona

Supporting data included counting the number of plants in 10 random 1 0-m row segments in each plot in the fall and in the spring. The spring count established that no winterkill had occurred and that our plantings were in reality 100, 77, 60, 45, 26, and 25% of full stand The 100% plot had 1,570,000 plants/ha. Approximately every other plant on the last plot was removed by hand-thinning in the spring, bringing that plot to about 12% of full stand

As often as possible, usually two or three times per week, 10 individual wheat plants were harvested (dug) from each plot to determine above ground dry-matter yield per unit area, which was calculated based on the stand count for each plot

To evaluate straw total–dry-matter relationships, straw and total dry-matter yield data for dryland winter wheat were collected from sources, for cultivars, and for treatments as given in Table 1 Linear regression analysis was employed to relate straw and total dry-matter production. Most of these data were from the Great Plains and most cultivars were of the hard red type, although some data from other locations and other cultivars were also included

Results and Discussion

In terms of total dry-matter production, there appears to be a general relationship between seasonal dry-matter accumulation for the six seeding rates and vegetation indices, as long as leafy material dominates the biomass (through end of tillering), as is shown in Fig. 1 for dry matter versus ND7 After tillering (ND7 $\simeq 0.5$) when stems become more dominant, the relationship collapses, eliminating reflectance ratios as predictors of

TABLE 1 Winter Wheat, Year, Location, Treatment, and Cultivars Used to Establish Relationship Between Grain and Total Dry-Matter Yields

Year	Location	Treatment Variable(s)	Cultivars	Reference
1956–1979	Akron, CO	Crop–fallow (no fertilizer used)	Comanche, Wichita, Warrior, Scout, Centurk	Greb, B W (personal communication)
1959, 1964–1966, 1976–1977	Colby, KS (Thomas, Logan, and Sheridan counties)	Cultivar, N, P, eroded soil, stubble mulch tillage	Buckskin, Centurk, Eagle, Bison, Larned, Lancota, Lindon, Sage	Sunderman, H (personal communication)
1963–1975	North Platte, NB	Bare and mulched soil, N	Lancer	Neghassi et al (1975)
1968–1971	Belgrade, MT	N–P, cultivars	Cheyenne, Delmar, Lancer, Crest, Itana, Rego, Winalta, Turkey, Gaines, Nugaines, Warrior, Froid, MT 6928	Brown, P L (personal communication)
1971–1972	Northeastern Montana	Grass barriers	Froid	Aase and Siddoway, (1974)
1972	Northeastern Montana	Spring clipping–regrowth	Froid	Aase and Siddoway, (1975)
1972–1973, 1975	Bushland, TX	Continuous dryland, dryland alternated with irrigated, tillage	Tascosa	Unger (1977)
1972, 1978	Northeastern Montana	Stubble, fallow, N–P–K, Residual P	Roughrider	Black (personal communication)
1973–1974	Northcentral Montana	Grass barriers, crop rotation, N–P–K	Wanser	Black, A L (personal communication)
1974–1975	Northcentral Montana	Crop rotation, tillage, herbicides, N	Cheyenne, Winalta	Brown, P L (personal communication)
1975–1976	Sidney, MT	Stubble, recrop	Froid, Winalta	Aase and Siddoway, (1980a), and unpublished data
1977	Sidney, MT	N–P, cultivars, seeding rate	Bezostaya, Mironovskaya, Roughrider	Black, A L , Aase, J K , and Siddoway, F H (unpublished data)

seasonal progression of total dry-matter production. Aase and Siddoway (1981) found the same relationship for spring wheat.

Next, we related vegetation indices, calculated from reflectance values obtained during the growing season, with straw and total dry matter at maturity A summary of these comparisons are found in Table 2. The r^2 values were generally somewhat higher for ND7 versus straw and total dry matter as compared with MSS7/MSS5 versus straw and total dry matter. The lower r^2 values associated with 9–15 May sampling dates were apparently due to haze and high cirrus clouds that interfered with the solar beam on those days.

The r^2 values (Table 2) from late tillering (stage 5) to approximately completion

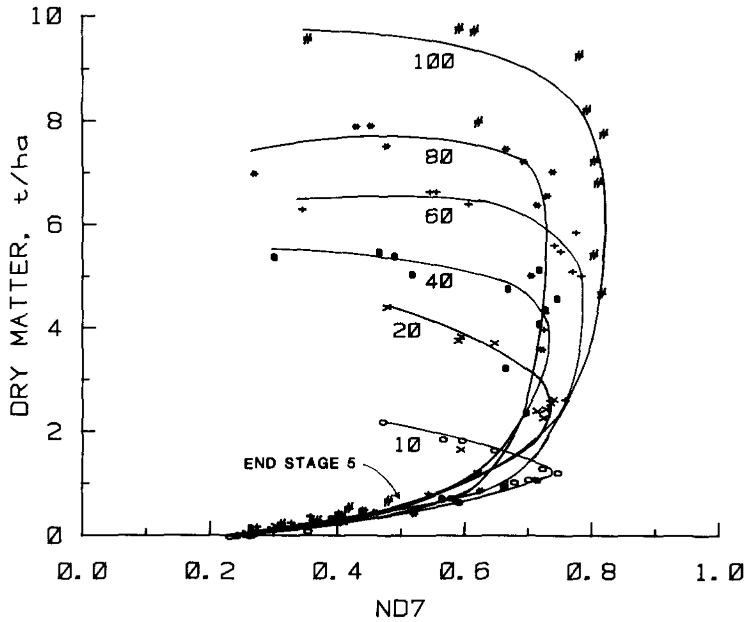

FIGURE 1 Normalized difference vegetation index [ND7 = (MSS7 − MSS5)/(MSS7 + MSS5)] vs total winter wheat dry matter for six seeding rates 10, 20, 40, 60, 80, 100% (100% = 67 kg/ha)

of flowering (stage 10.5 2) were higher than about 0.7 for both straw and total dry matter, suggesting that during this period rather accurate estimates of end-of-season total above-ground dry-matter production may be obtained. The relationship, as measured by r^2 values, started to decline after heading. The wheat was approximately three quarters headed on 14 June and the relationships between total dry matter versus MSS7/MSS5, total dry matter versus ND7, straw versus MSS7/MSS5, and straw versus ND7 are illustrated in Fig. 2 for this date

When we compared the data in Table 2 with similar data for a spring wheat experiment reported by Aase and Siddoway (1981), it was apparent that the relationship between dry-matter production and vegetation index broke down at an earlier growth stage for the winter wheat as compared with the spring wheat. The reason for the disparate results is the differential rate of color change within spring and winter wheats in the two experiments The color change due to ripening occurred later for 10% and 20% winter wheat plots than for the >20% plots, whereas the color change was more uniform among all rates for the spring wheat plots. This caused higher normalized difference vegetation indices for the low-seeding rate winter wheat plots (Aase and Siddoway, 1980b), resulting in the early (stage 10.5 2–10 5.4) collapse of the dry matter–vegetation index relationship as shown in Table 2 This explanation agreed with findings of other researchers who have reported that currently used remote sensing techniques are not sensitive to dead vegetation, stems, or nongreen leaf components of plant canopies (Holben et al , 1980, Tucker, 1977, 1979)

Our results suggest that dry-matter yield estimates may be obtained remotely This type of information can be

TABLE 2 Linear Regression (Least Squares) of Total Dry Matter and Straw at Maturity and Two Vegetation Indices at Various Stages of Growth. Curve Type: Yield $(t/\text{ha}) = m + b \times \text{VI}$

Date of Reflectance Measurements, (1978)	Growth Stage (Feekes)		ND7 Intercept	ND7 Slope	ND7 r^2	MSS7/MSS5 Intercept	MSS7/MSS5 Slope	MSS7/MSS5 r^2
Total Dry Matter								
26 April	3	Tillers formed	−9.38	55.30	0.687	−17.86	13.39	0.651
2 May	5	Leaf sheaths strongly erected	−7.30	42.05	0.807	−12.56	9.51	0.784
9 May	5–5.5	Leaf sheaths strongly erected	−6.31	34.33	0.712	−8.83	6.87	0.683
13 May	6	First node of stem visible	−4.42	28.80	0.671	−7.07	5.94	0.657
15 May	6	First node of stem visible	−3.81	24.43	0.743	−4.01	4.09	0.720
20 May	6–7	First & second node of stem visible	−5.43	21.76	0.899	−2.11	2.30	0.924
12 June	9–10.1	Ligule of last leaf visible to first ears just visible	−16.32	31.88	0.933	−1.48	1.18	0.903
14 June	10–10.4	Ear swollen but not visible to 3/4 headed	−15.67	31.97	0.946	−1.30	1.27	0.891
20 June	10.4–10.5.1	3/4 headed to beginning of flowering	−42.51	65.70	0.823	−5.71	1.68	0.760
21 June	10.4–10.5.2	3/4 headed to flowering complete	−40.66	61.88	0.755	−5.81	1.56	0.723
23 June	10.5–10.5.2	All ears out of sheath to flowering complete	−32.68	52.68	0.717	−4.77	1.55	0.688
27 June	10.5.2–10.5.4	Flowering complete to kernel watery ripe	−5.52	16.07	0.066	0.30	0.89	0.137
28 June	10.5.3–10.5.4	Flowering over at base of ear to kernel watery ripe	−11.09	23.01	0.090	−2.89	1.24	0.233

used to make management decisions regarding residues needed for incorporation in the soil, to manage residues for erosion control, and to determine potential excess residues for feed, energy or other needs. Residue yields have been estimated from grain production by assuming a constant straw:grain ratio (Turelle, 1963). However, straw:grain ratios are highly variable within and among years, geographical location, and management treatments, as was demonstrated by Bauer and Zubriski (1978) for spring wheat.

In Fig. 3, is shown the scatter of data points for straw:grain ratios versus grain yields for winter wheat with consequent

TABLE 2, continued

Date of Reflectance Measurements, (1978)	Growth Stage (Feekes)		Vegetation Index					
			ND7			MSS7/MSS5		
			Intercept	Slope	r^2	Intercept	Slope	r^2
Straw								
26 April	3	Tillers formed	−5.01	28.83	0.744	−9.46	7.00	0.710
2 May	5	Leaf sheaths strongly erected	−3.88	21.80	0.865	−6.63	4.94	0.844
9 May	5–5.5	Leaf sheaths strongly erected	−3.44	18.00	0.780	−4.80	3.62	0.755
13 May	6	First node of stem visible	−2.49	15.21	0.746	−3.91	3.14	0.733
15 May	6	First node of stem visible	−2.12	12.78	0.811	−2.24	2.14	0.790
20 May	6–7	First and second node of stem visible	−2.84	11.14	0.939	−1.12	1.17	0.955
12 June	9–10.1	Ligule of last leaf visible to first ears just visible	−8.09	15.86	0.920	−0.66	0.58	0.870
14 June	10–10.4	Ears swollen but not visible to 3/4 headed	−7.77	15.92	0.935	−0.58	0.63	0.859
20 June	10.4–10.5.1	3/4 headed to beginning of flowering	−20.50	31.85	0.771	−2.64	0.81	0.706
21 June	10.4–10.5.2	3/4 headed to flowering complete	−19.46	29.80	0.698	−2.63	0.75	0.659
23 June	10.5–10.5.2	All ears out of sheath to flowering complete	−15.33	24.99	0.643	−2.08	0.73	0.612
27 June	10.5.2–10.5.4	Flowering complete to kernel watery ripe	−1.05	5.68	0.033	0.71	0.36	0.089
28 June	10.5.3–10.5.4	Flowering over at base of ear to kernel watery ripe	−3.56	8.86	0.053	−0.87	0.54	0.178

poor predictability of residue levels. This data scatter resembled that presented by Aase and Siddoway (1981) for spring wheat. Most of the data in Fig. 3 are from the Great Plains (see Table 1) and have particular importance for the United States, since the Great Plains accounts for nearly 60% of the U.S. winter wheat production.

Little was gained by plotting straw:grain ratios versus total dry matter (not shown), however, when we plotted straw versus total dry matter, we found a good linear relationship (Fig. 4). This type of relationship was expected, and it explains why we obtained similar r^2 values for both straw and total dry matter as in Table 2. The straw–total-dry-matter rela-

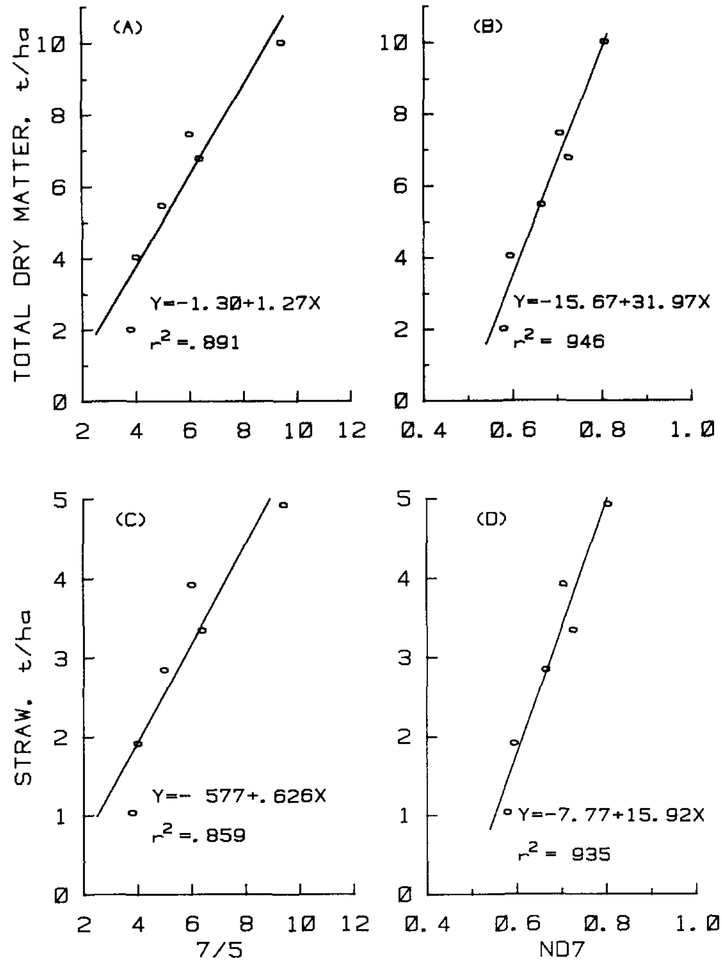

FIGURE 2 Band ratio MSS7/MSS5 and normalized difference vegetation index (ND7) on 14 June 1978 vs end-of-season straw and total dry-matter yields

tionship is uniform over a wide range of conditions. The slope of the regression line shown in Fig. 4 may be termed a "residue" index because of its similarity to the harvest index (Donald, 1962). The harvest index is formed by plotting grain yield versus total dry matter. When we did so, $r^2 = 0\ 856$ (data not shown), a respectable value, nevertheless a full 10 percentage points below that in Fig. 4. Depending on the growth stage, grain production is more sensitive to environmental stress conditions than is straw production, a fact illustrated by the data set from Neghassi et al. (1975) who identified high stress conditions in late June 1963 (about end of flowering), caused by high winds and temperatures, which resulted in particularly low harvest index values The effect on the "residue" index was minor

The data shown in Fig. 4 represent a wide range of climatic, geographic, and management conditions — from high fertilizer rates and unusual amounts of rainfall to no-till seeding and wheat grown

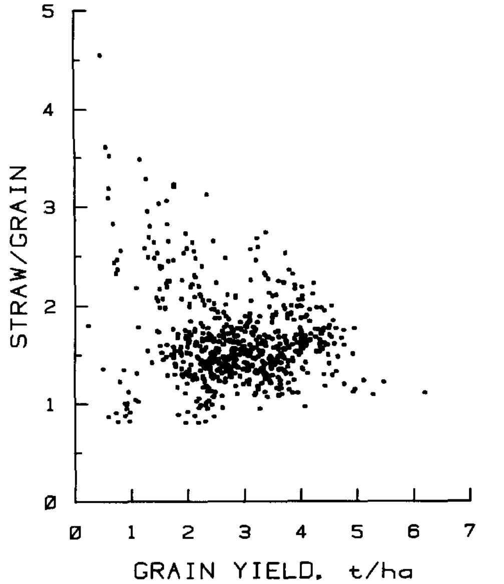

FIGURE 3 Straw grain ratios vs grain yield for several winter wheat cultivars grown at a wide variety of locations and conditions

on eroded soil Certain conditions such as hail, disease, and insect damage could cause wide deviations from the average As pointed out by Aase and Siddoway (1981), prudence must be exercised when interpreting data as in Fig. 2, since the validity of the relationships shown hinges on the assumption that nothing interferes with the "usual" or "customary" growth process Should any interference be encountered, such as severe drought stress or any damage from other factors, an accurate predictive value such as suggested may be invalidated Weed infestations can certainly falsify any estimates of straw production since weeds will appear as dry matter

Conclusion

Vegetation indices formed from spectral reflectance measurements of winter wheat from late tillering to beginning of flowering growth stages may potentially be used to predict end-of-season straw and total dry-matter production One must exercise caution to guard against misinterpretations that may be caused by weed infestations, disease, and other damage. These type of data can be important for inventorying biomass, for

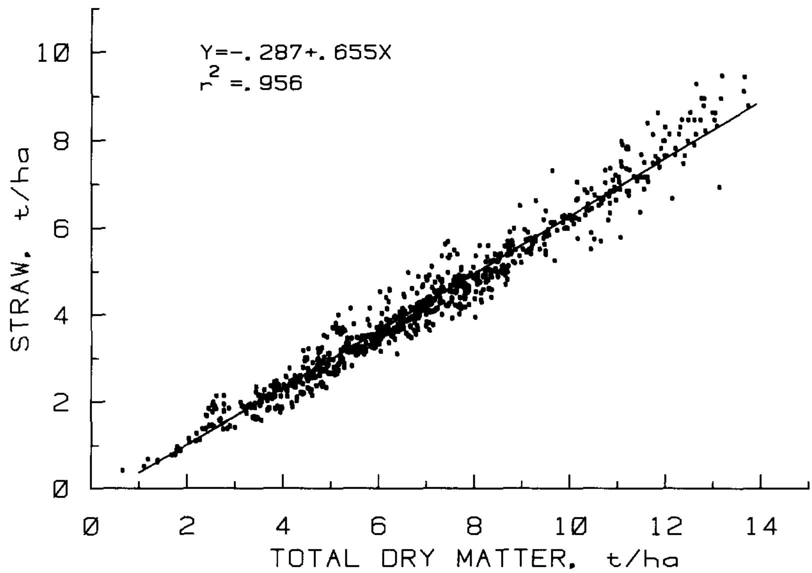

FIGURE 4 Same data as in Fig 3 plotted as straw vs total dry matter

making land management decisions regarding the return of organic matter to the soil, for controlling erosion, and for assessing crop residue yields that may be available for other purposes

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